

Numerical Modelling of Semi-rigid Connection with High Strength Steel

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Abstract

This work offers a three-dimensional finite element model of a flush end plate connection and the full interaction between plate columns is simulated by contact element using ANSYS 10.0 software aid. The analysis results of the moment-rotation relationship and behaviour characteristic of the connection with high strength steel are compared and discussed. The moment capacity prediction of flush end plate connections based on EC3 has been shown to be reasonable compared with finite element (FE) modeling. The proposed FE connection model is capable of predicting the ultimate load capacity and the plastic strain pattern with good accuracy. The model presented gives excellent results for increasing the connection capacity significantly due to employed higher strength steel section. The four parameter model is proposed to predict $M-\theta$ model through curve fitting for FEP connection with high strength end-plate.

Keywords

Flush End Plate; High Strength; Failure Mode; Moment-Rotation

Introduction

Numerical modelling by finite element analysis of beam-column connection has been done by many researchers. Three dimensional finite element (FE) models have been well verified with experimental results. More recent studies using FE modelling have focused mostly on top-and-seat angle and end plate connections. FE model from Bose et al. (1996), Bursi et al. (1998), Maggie et al. (2005) have been considered by solid elements, whilst Bahaari et al. (1996) and Shearbourne et al. (1996) have proposed model with shell elements. Danesh F, et al. (2007) consider a top and seat angle without web angle connection under effect of shear force on the initial stiffness. Taufik and Xiao (2005) have studied the behaviour of angle bolted connection by applying high strength steel with shell element model. There is a very little information about the beam-column bolted connection with high strength steel, which Puthli et al. (2001) and Moze et al. (2005) have been only pointed out experiment testing on simple bolted connection.

In this study, a refined 3D modelling of bolted connection are performed recognizing contact effects and bolt geometry. Since the pretension of the bolts and slip are most important parameters of connection behaviour by Citipitouglu et al. (2002), therefore the bolt model and contact element require considered model as accurate as possible. The modelling approach is still required simplifications by a half model in order to reduce the computational effort. Solid elements with symmetrical boundary condition are considered in order to eliminate generating various types of detailed 3D geometries. The model of shank and bolt hole is introduced for refining previous model as conducted by previous finite element modelling. Moze et al. (2005) produced experimental testing data on high strength steel. Taufik et al. (2011) investigated behaviour of partially restrained connection with high strength steel with refined four parameter power model to predict $M-\theta$ model through curve fitting. Taufik et al. (2006) conducted simplified finite element modelling of beam-column bolted connection with shell element. Various grades of high strength steel end-plates are simulated to investigate the connection behaviour.

Taufik et al. (2006) investigated behaviour of flush end plate connection with high strength steel using three-dimensional finite element modelling. Various grades of high strength steel end-plates are simulated to investigate the connection behaviour. Balc et.al (2012) presents the analysis with finite elements of a steel joint with end plate and prestressed bolts, using the ABAQUS finite element software code. The results obtained after the numerical simulation were compared with the experimental data in order to validate the model. Fanning et al. (2000) investigated behaviour of semi-rigid bolted end-plate connections with nonlinear finite element analysis.

Connection Configuration

Flush end plate (FEP) connections are designated in

provision of semi-rigid connection. FEP connection is able to transfer not only the vertical reaction but also some end moment of the beam to the column. The geometry of the FEP is based on two different sizes of beams and columns with all the connection parts are kept in same size, whilst the end-plates are clamped on column flanges. The only higher strength of the end-plate is applied to keep the original connection geometry for improving the moment and rotational capacity, whilst the other connection members are kept with carbon steel. The FEP connection parameter is depicted in TABLE 1. The configuration detailing of FEP connection in the non-linear finite element modelling is illustrated in FIG. 1.

TABLE 1 FEP CONNECTION PARAMETERS

Type	Beam	End-plate	Bolt - grade	g (mm)	p (mm)	r (mm)
FEP-1a	IPE240	268x160x t_{ep}	M20 – 10.9	98	158	55
FEP-2a	406x178UB	460x200x t_{ep}	M24 – 8.8	90	286	110
FEP-3a	HE320A	360x300x t_{ep}	M24 – 8.8	150	160	100

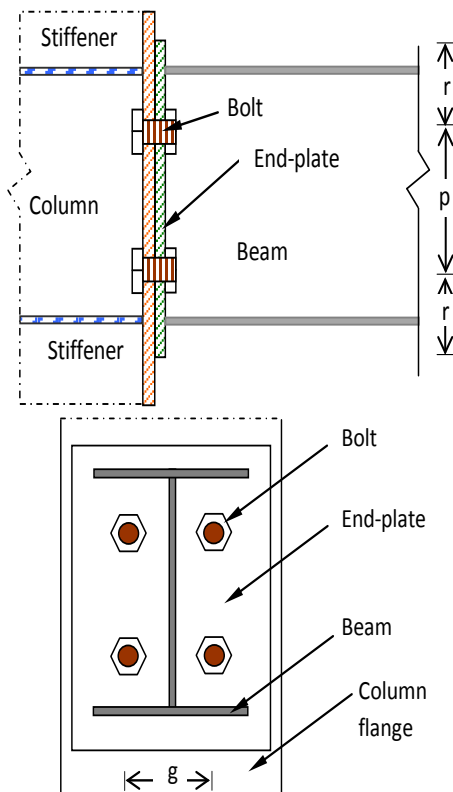


FIG. 1 FE MODELLING CONFIGURATION OF THE FEP CONNECTION

Steel material properties for FE analysis is based on experimental data. All steel materials for connection used are S275, M24 bolts grade 8.8 and M20 bolts grade 10.1, except for FEP-3a using S355 column and

beam, and S690 endplate as shown in TABLE 2. The FE analysis results of the FEP connection are presented in comparison with the test results. Comparisons are made with experimental results obtained from Simões da Silva et al. (2001), Bose (1998), and Coelho et al. (2001). The connection geometry is shown in FIG. 2, and the connection parameter is detailed in Table 2. Beam and column for FEP-1a are designated as IPE240 and HEA240, respectively, whilst 406x178x60UB and 254x254x 73UC are used for FEP-2a, and HE320A and HE300M are used for FEP-3. Bolt gauge on column flange (g) and bolt spacing (p) are 98.0 mm and 158.0 mm for all type FEP connections, except 150 mm, and 160 mm for FEP-3.

TABLE 2 MATERIAL PROPERTIES FOR FE MODEL

Specimen	Steel grade	f_y (MPa)	σ_{fu} (MPa)	f_y/f_u
column (1-2)	S275	340	520	0.654
beam (1-2)	S275	360	530	0.679
column (3)	S355	450	580	0.776
beam (3)	S355	450	580	0.776
bolt (1)	Grade10.9	1010	1108	0.912
bolt (2)	Grade 8.8	810	900	0.900
bolt (3)	Grade 8.8	840	940	0.894
end-plate (1-2)	S355	380	540	0.704
end-plate (hss-1)	S550	575	640	0.898
end-plate (hss-2)	S690	698	749	0.950

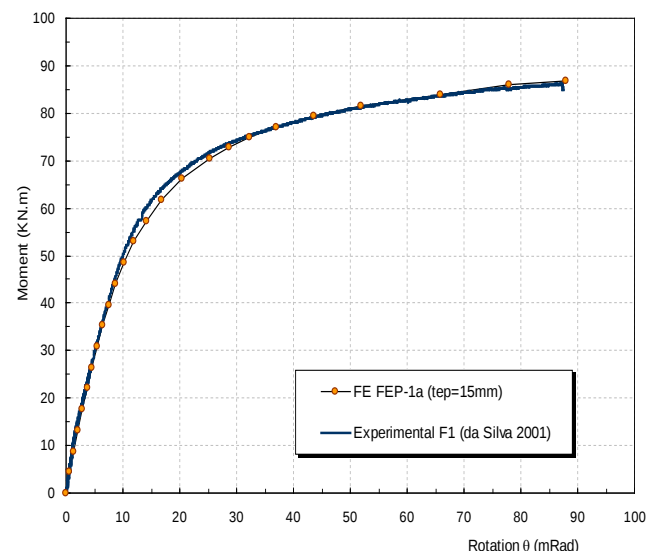


FIG. 2 VALIDATION OF FE MODELLING AGAINST TEST RESULT; FEP-1A CONNECTION

Different thickness of higher strength end-plate (t_{ep}) are applied. The end-plates are determined with different high strength steel grade, whilst the beam

and column are kept to mild carbon steel. TABLE 3 shows the configuration of finite element model for the FEP connections.

TABLE 3 FEP CONFIGURATION PARAMETER FOR FEA

Connection destination	Beam size	Stiffener (mm)	Plate grade	t_{ep} (mm)	g (mm)	p (mm)
FEP-1a	IPE240	N/A	S550	15.0	98.0	158.0
FEP-1b	IPE240	10.0	S550	15.0	98.0	158.0
FEP-1c	IPE240	N/A	S690	15.0	98.0	158.0
FEP-1d	IPE240	10.0	S690	15.0	98.0	158.0
FEP-1d*	IPE240	10.0	S690	12.0	98.0	158.0
FEP-1e*	IPE240	10.0	S550	15.0	98.0	158.0
FEP-1f*	IPE240	10.0	S690	15.0	98.0	158.0
EP-1g*	IPE240	10.0	S550	18.0	98.0	158.0
FEP-2a	406x178UB	N/A	S550	15.0	98.0	158.0
FEP-2b	406x178UB	10.0	S550	15.0	98.0	158.0
FEP-2c	406x178UB	N/A	S690	15.0	98.0	158.0
FEP-2d	406x178UB	10.0	S690	15.0	98.0	158.0
FEP-3a	HE320A	N/A	S690	10.0	150.0	160.0
FEP-3b	HE320A	N/A	S690	15.0	150.0	160.0
FEP-3a*	HE320A	N/A	S690	10.0	150.0	160.0
FEP-3b*	HE320A	N/A	S690	15.0	150.0	160.0

$r = 55$ mm for FEP-1 and FEP-2, and $r = 100$ mm for FEP-3

Numerical Modelling

The ANSYS version 10.0 which is a general purpose finite element package is selected to carry out numerical modelling analysis (ANSYS, 2004). Non linear flush end plate connection model is symmetric about the centre of the beam web and no lateral displacement is assumed, so only one side of the plane of symmetry is modelled. The geometry of the model now represents one half of the full scale connection in the terms of area and moment of inertia, so the capacity of the connection model is only a half of the actual load capacity.

The following ANSYS element types are used for only one half of an entire flush end plate connection. Eight node isoparametric plastic solid elements, SOLID45, are used to model beam, column and end-plate. Bolt head and nut are idealized using eight-node isoparametric solid elements, i.e. SOLID45. Bolt shank is modelled using twelve 3D spar element of LINK8

elements. The interactions between angle and column or beam are simulated by CONTACT178 elements. The bolt head and nut are modelled as hexagons. The bolt shank is modelled using spar element connecting the farthest corner nodes of head and nut to each other. The effective area of the bolt is split one twelfth equally among the spar elements. The bolt holes are modelled as circular in M22 diameter holes. Bolt pretension caused by bolt tightening is simulated by applying equivalent initial strains for bolt shank elements. Initial strain value of bolt pretension is used according to the bolt pretension calibration curves as designated by Citipitiouglu et al. (2002). Since the bolt is tightened, the head and/or nut stay in close contact with their connecting angles and flanges, therefore the bolt share their nodes with the plate ones.

Interface element is considered to accommodate the effect of friction and slip. Friction coefficient value is used to capture experimental response and previous FE modelling. The model of interface element is designated as a line of 3D node to node contact element with coincident nodes. The interface elements connect the nodes at the back of the end-plate to corresponding nodes at the column flange.

The external monotonic static point load is applied in increments to obtain a converged solution to a nonlinear analysis. The automatic time stepping is on with the minimum time step increment is set for gaining load sub step result at the last step. The convergence criterion is based on the force and displacement for tracking the maximum plastic strain step. The deformation measurement is based on the deformation of the angle. The relative displacements at the locations of the beam tension and compression flanges were used to find the rotation of a connection. The rotation of connection is defined as relative horizontal displacement over the depth of the beam measured from the centre of top flange to the centre of bottom flange. The most important aspect of semi-rigid connection behaviour is the moment-rotation ($M-\theta$) relationship. Flush end plate connections represents flexible connection due to the geometry displacement of end-plate. The moment rotation curve of the connection is based on the simple relations: $M = Fd$, $\theta = \arctan h$ where M is the moment, θ is the rotation of the connection, F is twice as much as the applied point load, d is the length of the beam, is relative displacement of the beam and h is the depth of the beam measured from the centre of top flange to the centre of bottom flange. The finite element models were validated against the recorded load-

displacement curves from the tests.

As the initial stiffness of the endplate connection is governed by the geometry of the endplate, the non-linear behaviour is related to material properties. To establish the effects of end-plate configurations, plate thickness and strength are selected as two main parameters. Multi-linear elastic-plastic approach is used to determine the material properties of high strength steel for the FE model, whilst the yield stress is defined as 0.2% proof stress. By these parameters combination, various moment-rotation curves can be obtained from 3D nonlinear finite elements analyses. In order to increase the connection capacity, the higher strength end-plates are applied with different thickness. Bolt gauge, bolt spacing and bolt diameter are kept in the same value. Plots of the Von Mises equivalent stress and plastic strain were used to assess the predicted yield line patterns.

Mild carbon steel S275 was used for beams and column with yield stress of 300 MPa and Young modulus of 210 GPa. High strength bolts of M20 and M24 grade 8.8 with yield stress of 800 MPa are applied for all types of connections. Multi-linear elastic-plastic approach is used to determine the material properties of beam, column and angle for the FE model. Multilinear elastic-plastic approach is used to determine the material properties of high strength steel for the FE model, whilst the yield stress is defined as 0.2% proof stress. Material properties of carbon steel grade S355 and high strength steel grade S550 (hss-1) and S690 (hss-2) are used for the FE models as depicted in Table 2, whilst a Poisson's ratio is 0.3.

The FEA results are shown in Figures 5 to 8. A close correlation between the model and test was observed, with a good comparison of the stiffness and moment-rotation capacity. The analysis result of the FEP connections is presented in Figures 2, 3, and 4. The FE models show ultimate moments of 87.2, 166.5, 130.5 and 210.0 kN.m, respectively.

FIG. 4 shows different shape of $M-\theta$ curve compared with Figures 2 and 3, which it was considered local softening effect after ultimate moment reached.

Comparison between the Finite Element Analysis and test results for the FEP connections is presented in TABLE 4. The FEA results are shown in FIG. 5 to 8. A close correlation between the model and test was observed, with a good comparison of the stiffness and

moment-rotation capacity. The analysis result of the FEP connections is presented in Figures 5 to 8. The FE models show ultimate moment of 87.2 kN.m, 166.5 kN.m, 130.5 kN.m and 210.0 kN.m, respectively. Comparison between the FEA and test results for the FEP connection is presented in TABLE 4.

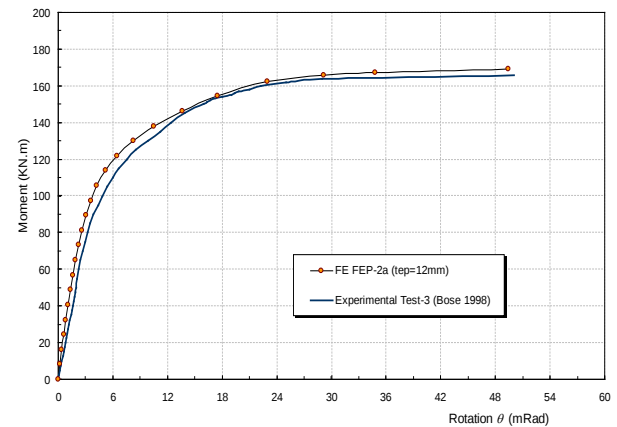


FIG. 3 VALIDATION OF FE MODELLING AGAINST TEST RESULT – FEP-2A

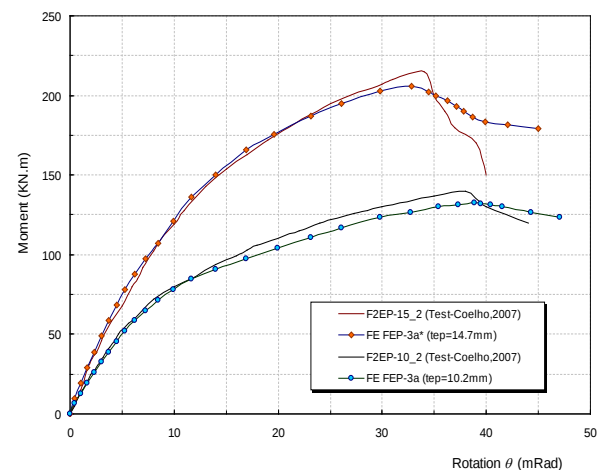


FIG. 4 VALIDATION OF FE MODELLING AGAINST TEST RESULT – FEP-3A

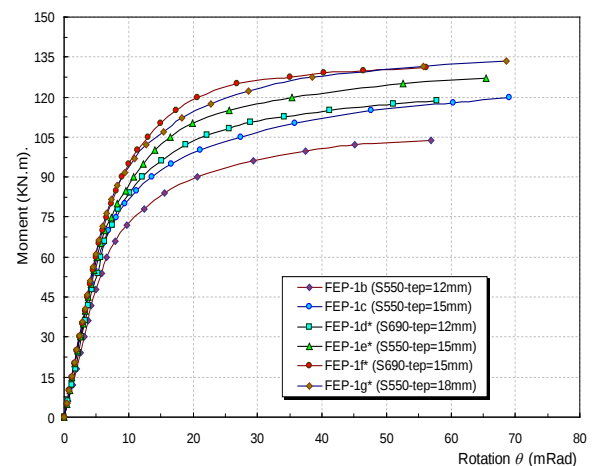


FIG. 5 MOMENT-ROTATION RELATIONSHIP OF THE FEP-1 MODEL; M22 BOLTS

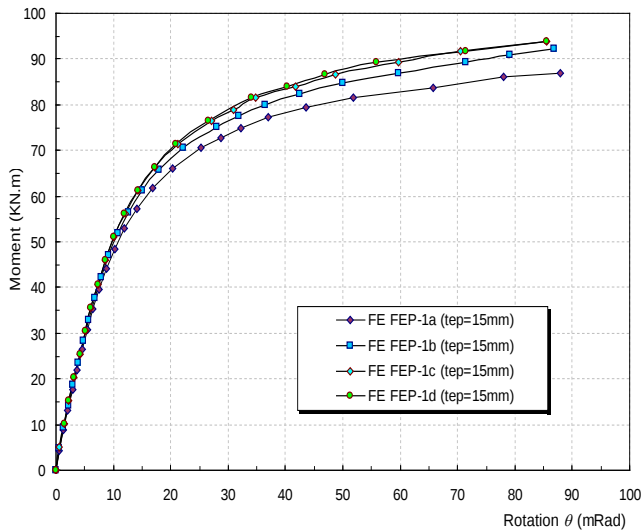


FIG. 6 MOMENT-ROTATION RELATIONSHIP OF THE FEP-1 MODEL; M20 BOLTS

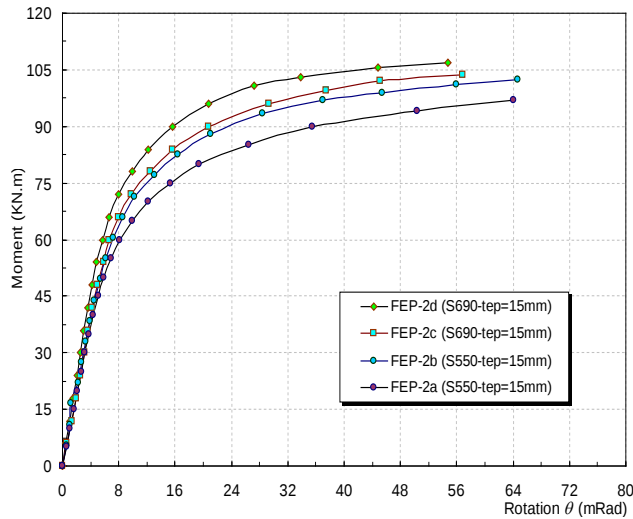


FIG. 7 MOMENT-ROTATION RELATIONSHIP OF THE FEP-2 MODEL; M20 BOLTS

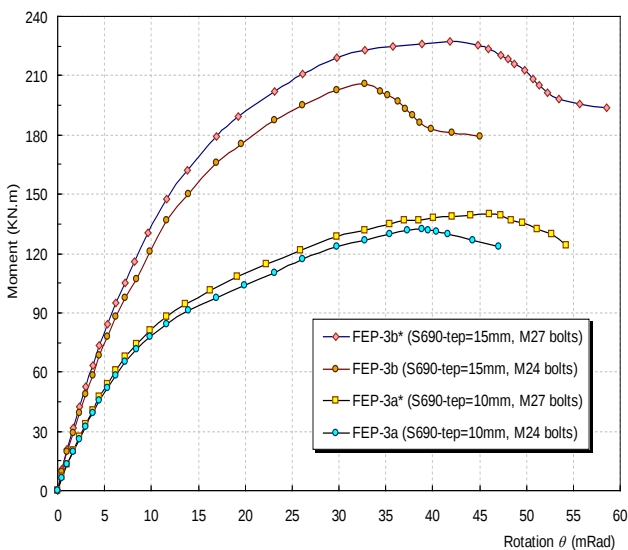
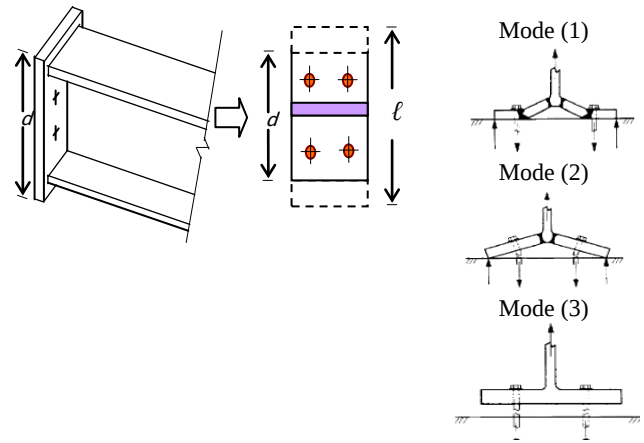


FIG. 8 MOMENT-ROTATION RELATIONSHIP OF THE FEP-3 MODEL; M24 BOLTS

TABLE 4 COMPARISON FEA AGAINST TEST RESULTS

Connection	FEA result			Test result		
destination	R_{ki}	M_u	θ_{Mu}	R_{ki}	M_u	θ_{Mu}
FEP-1a	7.96	87.2	88.0	7.85	86.5	88.0
FEP-2a	46.38	166.5	49.5	40.00	165.0	50.0
FEP-3a	21.57	130.5	39.0	19.00	140.0	38.0
FEP-3a*	14.39	210.0	32.5	14.00	218.5	34.0

R_{ki} in kN.m/mRad; M_u in kN.m ; θ_{Mu} in mRad

FIG. 9 EFFECTIVE LENGTH ℓ_{eff} OF EQUIVALENT T STUB AND THREE POSSIBLE MODES OF YIELDING

The FEP connections based on FEM with stiffened and un-stiffened column are also analyzed using design equations to modern design codes EC3 (CEN, 1993). The design tension resistance of the column flange and of the end-plate are given in terms of equivalent T-stub. The effective length ℓ_{eff} of plate and column flange is based on the yield line patterns around bolt holes and should be taken as the height of the end plate d as shown in FIG. 9. The smallest value for the three possible modes of the yielding is chosen from equation 1, 2 and 3 as follows:

$$F_{t,Rd} = \frac{4(0.25\ell_{eff}t_y^2 f_y / \gamma_{M0})}{m} \quad (1)$$

$$F_{t,Rd} = \frac{2(0.25\ell_{eff}t_y^2 f_y / \gamma_{M0}) + n\Sigma B_{t,Rd}}{m + n} \quad (2)$$

$$F_{t,Rd} = \Sigma B_{t,Rd} \quad (3)$$

Determine the design value of the moment resistance of the connection M_{Rd} based on the bolt-rows in the reduced tension zone, from:

$$M_{Rd} = F_{ti,Rd} \left(\frac{\Sigma h_i^2}{h_1} \right) \quad (4)$$

Moment connection capacity of the FE result and the EC design prediction for high strength FEP connection has been compared. The comparisons of the ultimate moment from FEA with different steel grade of end-plates are made within stiffened (s) and unstiffened column (n). TABLE 5 indicates the observed failure moments from the FE analyses, compared with the design predictions. Plots of von Mises' stress contours of the FEP connection with S275 and S355 column are shown in Figures 10 and 11. A significant change of maximum stresses shows the value of 954.603 MPa to 978.041 MPa, respectively.

TABLE 5 ULTIMATE MOMENT AND FAILURE MODE OF FEP MODEL

Connection destination	Column (stiffened)	End-plate (mm),grade	M_{ult} (FE) (kN.m)	M_{ult} (EC3) (kN.m)	failure mode
FEP-1a	S275 (n)	15.0, S550	96.0	80.2	cf(2)
FEP-1b	S275 (s)	15.0, S550	102.3	81.7	cf(2)
FEP-1c	S275 (n)	15.0, S690	103.8	80.2	cf(2)
FEP-1d	S275 (s)	15.0, S690	106.8	81.7	cf(2)
FEP-1d*	S275 (s)	12.0, S690	107.0	91.3	cf(2)
FEP-1e*	S355 (s)	15.0, S550	127.0	95.4	ep(2)
FEP-1f*	S355 (s)	15.0, S690	130.0	102.7	cf(2)
FEP-1g*	S355 (s)	18.0, S550	131.5	102.7	cf(2)
FEP-2a	S355 (n)	15.0, S550	97.0	80.2	ep(1)
FEP-2b	S355 (s)	15.0, S550	100.0	95.4	ep(2)
FEP-2c	S355 (n)	15.0, S690	104.5	95.4	cf(2)
FEP-2d	S355 (s)	15.0, S690	106.8	102.7	cf(2)
FEP-3a	S355 (n)	10.0, S690	132.6	104.8	ep(1)
FEP-3b	S355 (n)	15.0, S690	205.7	194.1	bf(2)
FEP-3a*	S355 (n)	10.0, S690	139.7	104.8	ep(1)
FEP-3b*	S355 (n)	15.0, S690	227.7	194.1	cf(2)

cf(2): column flange mode 2; ep(1) (2): end plate mode 1 or 2; bf(2): bolt failure mode 2

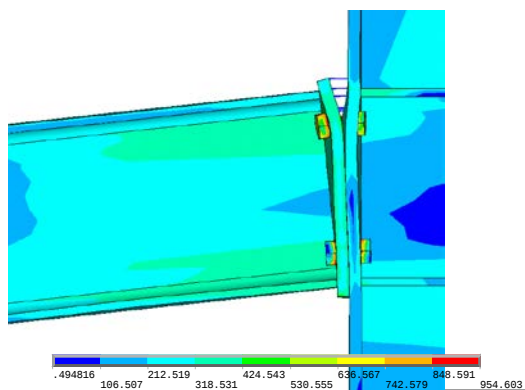


FIG. 10 STRESS CONTOURS OF THE FEP MODEL WITH S275 COLUMN; UNIT IN MPA

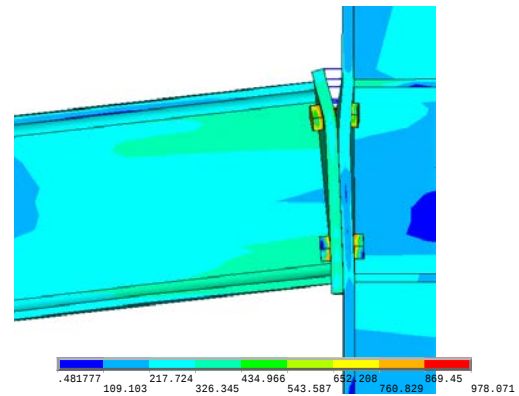


FIG. 11 STRESS CONTOUR OF THE FEP MODEL WITH S355 COLUMN; UNIT IN MPA

From the results in TABLE 5, it can be seen that the designs are somewhat conservative despite the omission of factors of safety. The FE model of the FEP connection with thin end-plate and low beam depth shows significant results close to EC3 prediction, and also for connection with thicker end-plate and higher beam depth. Modern design methods such as EC3 use yield line analyses of the end plate to predict the capacity of the tensile region. At the ultimate load, the failure mode type (1) which is complete yielding of the column flange occurred for almost all of the FEP connection except for thinner S550 and S690 end-plate of the FEP connection on the end-plate. The finite element model was used to confirm the predictions by studying the yielding of the end-plate and column flange. Waiving of column web stiffeners is not advisable because their absence causes premature failure in the column flange. This consequently leads to a drastic drop in moment and rotation capacities. The ultimate moment of S690 15.0mm thick end-plate without column stiffener reached 96.0 kN.m, and it can be increased by 102.3 kN.m if the column stiffeners exist. However, a connection with column web stiffeners is advisable because their presence increases moment capacity up to 20%.

Plots of von Mises' stress contour of the FEP connection with the 15mm thick S690 end-plate and S355 column are presented in FIG. 12 and 13. Plastic deformation of S690 end-plate is shown in FIG. 14. The maximum stress of end-plate and the ultimate stress of closely reach the ultimate stress and also for the column flange stress. The ratio between maximum stress and the ultimate stress of the end-plate is 99.0%, whilst the ratio between maximum stress and the ultimate stress of the column flange is 86.0%. The effect of plate thicknesses gives significant change of the initial stiffness, whilst the thin higher strength end-plate will be more pronounced on the moment capacity of connection.

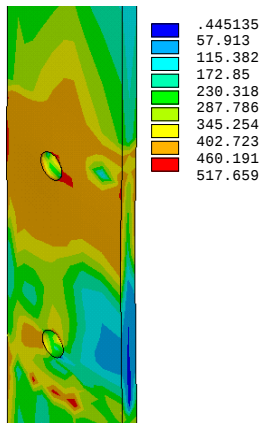


FIG. 12 STRESS CONTOUR OF THE S355 COLUMN FLANGE

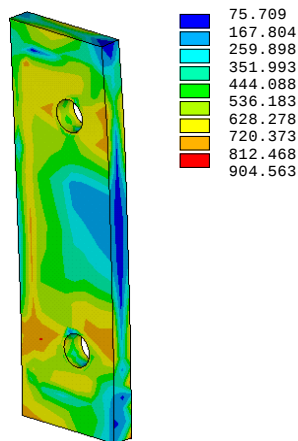


FIG. 13 STRESS CONTOUR OF THE S690 ENDPLATE

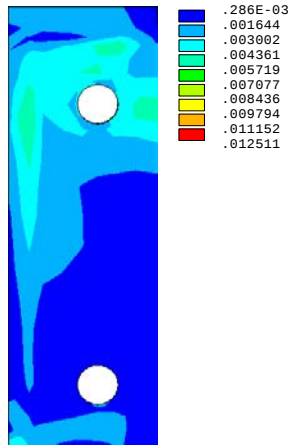


FIG. 14 PLASTIC DEFORMATION OF THE S690 END-PLATE

Analytical Model for Moment-Rotation

The stiffness of any semi-rigid connection is dependent upon the moment-rotation characteristic associated with the connection. Many attempts have been made to establish curve-fitting techniques that can be used to provide suitable models for semi-rigid connections. Abolmaali et.al (2005) have developed moment-rotation model equations for flush end-plate connections. It was shown that both models predicted the $M-\theta$ plots closely, with the more accurate model

being the Three-Parameter Power model. The Three-Parameter Power model was originally proposed by Richard and Abbott (1975) and Chen and Kishi (1989) to predict the moment-rotation ($M-\theta$) characteristics of PR connections.

The $M-\theta$ data points obtained from these analyses were curve fitted to Equations 5 and 6 by minimizing their error-square to obtain model parameters M_u , n , q , and θ_0 . Consequently, regression equations were developed for the aforementioned parameters of each equation in terms of geometric variables of the connection region. The three parameter is expanded into a proposed equation to accommodate change in the curve shape due to non-linear behaviour of different steel grade of each member of the connection as defined by Taufik et al. (2011). The rigidity parameter n is exploded into parameter q , with the dependent variables are considered, the prediction equations is defined as:

$$M = \frac{R_{ki} \theta}{\left[1 + (\theta / \theta_0)^n\right]^{\frac{1}{q}}} \quad (5)$$

where

M_u = ultimate moment capacity (kN.m)

n = rigidity parameter

q = rigidity parameter

R_{ki} = initial connection stiffness (kN.m/rad)

θ_0 = reference plastic rotation defined by:

$$\theta_0 = M_u / R_{ki} \quad (6)$$

In this study, several test cases selected using the FEM connection model developed in previous section. The $M-\theta$ data points obtained from the analysis were curve fitted to obtain model parameters. Consequently, regression equations were developed for the aforementioned parameters of each equation in terms of geometric variables of the connection region. In the development of the prediction equations, the independent variables (connection geometric variables) are defined as:

g = the gage distance

d_b = the nominal bolt diameter

p_t = the bolt pitch

h_b = the beam depth

t_{ep} = the thickness of end-plate

t_{cf} = the thickness of column flange

F_{yp} = material yield stress of end-plate

F_{yc} = material yield stress of column

Unit of independent variables: mm and N/mm²

Using these results and the multiple regression

technique, a prediction equation was developed for each independent parameter using the following general form:

$$R_{ki} = \prod_{j=1}^m A a_j^{w_j}; \quad M_u = \prod_{j=1}^m B a_j^{x_j};$$

$$n = \prod_{j=1}^m C a_j^{y_j}; \quad q = \prod_{j=1}^m D a_j^{z_j} \quad (7)$$

where A, B, C and D are unknown coefficients, a_j is the j th independent parameter, w_j , x_j , y_j , and z_j are the exponents to be determined through regression, and m is the number of independent parameters considered. Taking logarithms of both sides of the formulae in Equation (7), linear forms of these formulae are obtained as:

$$\ln R_{ki} = \ln A + \sum_{j=1}^m w_j \ln a_j \quad (8)$$

$$\ln M_u = \ln B + \sum_{j=1}^m x_j \ln a_j \quad (9)$$

$$\ln n = \ln C + \sum_{j=1}^m y_j \ln a_j \quad (10)$$

$$\ln q = \ln D + \sum_{j=1}^m z_j \ln a_j \quad (11)$$

Multiple regression using spreadsheet software is applied to each formula in Equations 8 to 11 to determine the coefficients A, B, C, D, w_j , x_j , y_j , and z_j . From regression analyses, Equations 12 to 15 represent independent parameters of the design equation for ultimate moment, reference plastic rotation, and rigidity parameter. Sensitivity and error band analyses were conducted to validate the behaviour of each equation to the variation of independent variables and the error associated with each equation, respectively.

The design equations for the four dependant parameters of the flush end plate connection based on Taufik et al. (2011) are obtained as:

$$R_{ki} = 162.02 g^{0.77} p_j^{1.28} d_b^{0.34} t_{ep}^{1.71} \text{ (N.mm/rad)} \quad (12)$$

$$M_u = 3.57 d_b^{0.76} t_{ep}^{0.82} h_b^{0.37} t_{ep}^{1.25} F_{yu}^{0.85} \text{ (N.mm)} \quad (13)$$

$$n = 21.22 d_b^{-0.25} p_j^{0.64} h_b^{-0.82} t_{ep}^{0.28} t_{cf}^{0.77} F_{yp}^{0.25} F_{yc}^{-0.24} \quad (14)$$

$$q = 23.01 d_b^{-0.25} p_j^{0.64} h_b^{-0.82} t_{ep}^{0.27} t_{cf}^{0.078} F_{yp}^{0.29} F_{yc}^{-0.28} \quad (15)$$

TABLE 6 below presented the parameter values for power model obtained through curve fitting for high strength FEP connection. Parameter n and q indicate rigidity parameters influenced by different steel grades of end-plate. Coefficient correlations r indicates level of accuracy of curve fitting from FEM results compared by proposed equations.

TABLE 6 PARAMETERS VALUES FOR POWER MODEL

Connection	R_{ki}	M_{uc}	n	q	r
FEP-1c	12.10	103.80	1.56	1.59	0.9995
FEP-1g*	18.50	133.62	1.60	1.62	0.9994
FEP-1d*	12.73	118.80	1.74	1.76	0.9992
FEP-2a	11.50	97.00	1.38	1.41	0.9993
FEP-2b	12.60	100.00	1.38	1.41	0.9992
FEP-2c	14.30	104.50	1.38	1.41	0.9991
FEP-2d	16.20	106.80	1.38	1.41	0.9992
FEP-3a	14.30	132.60	1.12	1.25	0.9991
FEP-3b	21.00	205.70	1.24	1.42	0.9992
FEP-3a*	14.88	139.70	1.18	1.28	0.9941
FEP-3b*	22.80	227.50	1.20	1.32	0.9885

n, q = rigidity parameter; r = coefficient correlation; R_{ki} in kNm/mrad; M_{uc} in kN.m

FIG. 15 shows comparisons between typical FEM $M-\theta$ results and the predicted proposed $M-\theta$ model values for each connection obtained from TABLE 4. It can be seen from these figures that the predicted curves give very close correlation with FEA results.

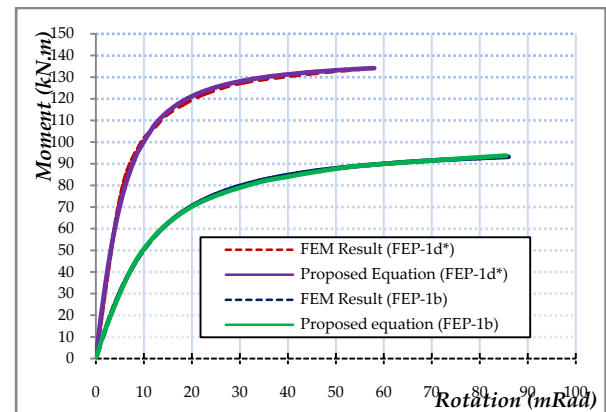


FIG. 15 FEM RESULTS VS PROPOSED EQUATIONS

Conclusion

A three-dimensional finite element model of a flush end plate connection is presented. Three different steel grades of end-plate properties are investigated. Conclusions are drawn based on the research.

- The high strength end-plate gives significant proportion of maximum stress distribution, whereas the beam and column are kept to mild carbon steel.
- The results obtained from the FEA for the moment-rotation curves of different specimens of end-plate connection are within the range of 3% to 5% compared to the experimental results.
- However, connection with column web stiffeners is advisable because their presence increases

moment capacity up to 15%.

- d) It can be observed that, if thickness of end-plate is bigger than the thickness of column flange, the moment capacity of the connection will not be increased in clearly due to excessive deformation of column flange and web.
- e) Thick high strength end-plate connections provide additional rotational stiffness and moment capacity but the rotation capacity may be compromised by bolt failure. This type of failure mode is not acceptable for semi-rigid frame design because a large rotation capacity is required to allow moment redistribution.
- f) The moment capacity prediction of EC3 has been shown to be reasonable. The nature of the failure mode was predicted reliably for the semi-rigid connections studied.
- g) A power model expression was proposed to predict the ultimate moment and initial stiffness of the high strength FEP connection. The expression is a function of the corresponding strength of the end-plate and column flange. A reasonably good prediction was obtained for high strength semi-rigid connection.

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 - "Computational Frame Analysis of Partially Restrained Connection with Strain Softening Effect", 2009
 - "Numerical Modelling of the Effect of Openings in the Composite Beam Flange to the Composite Connection", 2009
 - "Three-Dimensional Finite Element Modelling of Flush End Plate Connection with High Strength Steel", 2006